ESTIMATING FREE FIELD, FAR FIELD RADIATED NOISE SOURCE LEVELS FROM MEASUREMENTS ACQUIRED IN A HARBOR ENVIRONMENT

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ABSTRACT

The radiated noise of ships or other underwater sources are typically characterized in terms of a far-field, plane-wave equivalent source level based on measurements assumed to have been acquired in a free-field environment such as a deep water test range. Measurement of ship noise in a harbor environment, where multiple reflections, high background noise and short propagation paths are the norm, violates the conditions that assume the ship is a radiating simple source. Careful analysis is required to arrive at a valid estimate of far-field, free-field source levels from such measurements.

This work presents results from a test conducted at the US Navy Acoustic Research Detachment in Bayview, Idaho during summers 2010 and 2011. A line of omnidirectional hydrophones was deployed from a barge adjacent to a moored test vessel to obtain radiated noise measurements from several shipboard sources. A series of test signals was also transmitted through calibrated acoustic sources to evaluate the effectiveness of post-processing techniques, as well as line array beamforming, in minimizing reflected path contributions and improving signal-to-noise ratio. Methods of estimating far-field, free-field equivalent source levels based on these measurements are presented.

INTRODUCTION

Ship radiation, as well as other underwater sources, is typically characterized in a deep water environment using a far-field, free-field assumption, which is almost exclusively the only method covered in array signal processing literature. This assumption states that the ship is a radiating simple source and the wavefronts received by the array can be considered to be planar. Literature typically defines the far-field starting at

—

where r is the distance from the center of the array to the source, L is the largest dimension of the array, and λ is the operating wavelength.

Measurement in a harbor environment, however, violates these assumptions for frequencies in the range of interest and other signal processing methods must be explored. Therefore, we consider beamforming to reduce the multipath contribution to the signal as well as other background noise. This also allows us to take into account the spherical geometry of actual wavefronts.

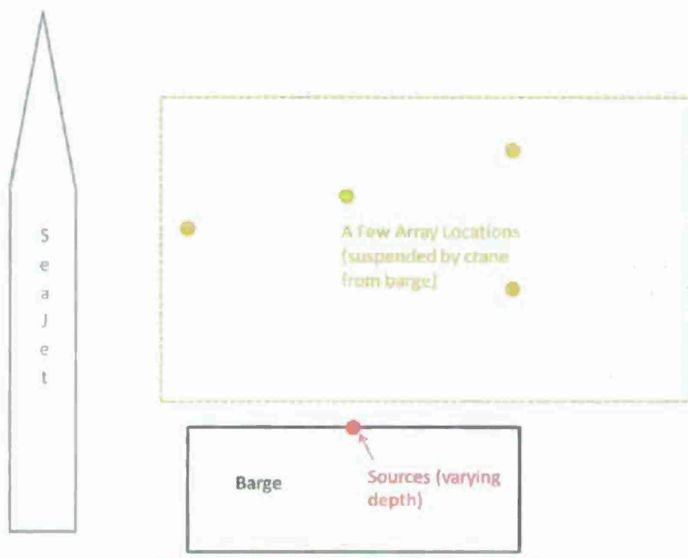

FIGURE 1. Research site geometry.

Lake Pend Oreille in Bayview, Idaho is one of the deepest lakes in the country, with a maximum depth of approximately 1200 feet. It is also home to a US Navy Acoustic Research Detachment (ARD). It is an ideal location for acoustic experimentation due to small amounts of boat traffic, making the ambient levels quite low. An array of 14 omnidirectional hydrophones was deployed off a barge next to a moored quarter scale DDG1000, the SeaJet, in a shallow (<50ft depth) harbor. Two sources were then lowered into the water column off the side of the barge and transmitted various test signals. The geometry of the environment is shown in Figure 1. These signals and measurements were used to obtain calibrated data in order to evaluate several post-processing techniques. This paper explores various methods of post-processing and their effectiveness in minimizing reflected path contributions as well as improving signal-to-noise ratio.

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OMNIDIRECTIONAL PROCESSING

An array of 14 omnidirectional hydrophones with 16 inch spacing between elements was deployed in both a harbor test as well as a deep water test in the lake. Basic signal processing was used to find third octave band levels. Using known depths and ranges, expected transmission loss can be calculated from these levels using the standard convention:

$$TL = 20\log(r)$$

Signals transmitted in the deep water tests hold very close to this convention, with test values falling within 1 dB re 1μPa of the expected value. This reveals that we are operating in the free-field, with very little to no contribution from reflections. This can be seen with a broadband noise signal plotted against the ambient in Figure 2a. Signals transmitted in the harbor tests, however, showed transmission loss lower than the convention, with test values being over 4 dB re 1μPa higher than the expected value. Tests done in the harbor environment are greatly contaminated by multiple reflections from not only the surface and the bottom, but also other underwater interfaces. This can cause many problems in determining an equivalent source level. This is shown in Figure 2b, where the same source was radiating the same power level over a slightly different range. A very different third octave band level, and therefore source level, can be observed between the far-field measurement and the measurement in the multipath environment.

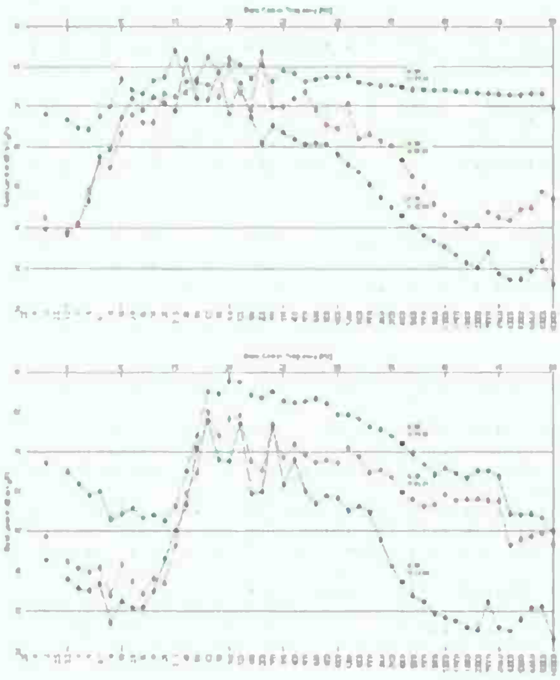

Figure 2. Broadband noise generated by a J9 omnidirectional source shown in one third octave band levels. Reference hydrophone one meter from the source (green), bottommost array hydrophone (red), ambient level (blue). The band of interest here is the 4 kHz band. Figure (a) depicts measurement in a deep-water environment with the expected 30 dB of transmission loss while Figure (b) depicts measurement in a shallow-water environment with 10 dB of transmission loss where 18 dB is expected.

LINEAR FAR-FIELD BEAMFORM PROCESSING

In far-field beamforming, we begin with a beamforming equation for array processing given in [1]:

$$p(r,\theta,t) = \sum_{i=1}^{N} \frac{A}{r_i'} e^{j(\omega t - k r_i')} \tag{1}$$

From this base equation, we make the assumptions that all r_i are approximately parallel, so

$$r \gg (N-1)d$$

and

$$\frac{1}{r_i} \cong \frac{1}{r}$$

for all i where r is the distance from array center to source. We also add a phase delay:

$$\phi_i = i\frac{2\pi}{\lambda}\Delta r = i\frac{2\pi}{\lambda} d\sin\theta_0 \tag{2}$$

where d is the element separation and θ_0 is the incident angle. With these assumptions, we arrive at a corrected equation:

$$p(r,\theta,t,\theta_0) = \frac{A}{r} e^{j(\omega t - kr)} e^{-j\left(\frac{N-1}{2}\right)k\Delta r} \sum_{i=1}^{N} e^{j(ikd\sin\theta_0 + [i-1]k\Delta r)} \tag{3}$$

where $\Delta r = d\sin\theta$.

This is very similar to equation (7.8.2) in [1] except with an added phase delay. Strict time-domain beamforming is not an option with this set of data because our resolution is not fine enough to establish a proper angle of incidence. So instead we turn to frequency domain beamforming. A Fourier Transform on this Eqn. (3) gives us the equation:

$$F(\omega) = \frac{A}{2\pi r} e^{-jkr} e^{-jk\Delta r\left(\frac{N-1}{2}\right)} \left(\sum_{i=1}^{N} e^{j(\phi_i + [i-1]k\Delta r)}\right) \int_{-T/2}^{T/2} dt \tag{4}$$

This is only $\sum_{i=1}^{N} e^{j\phi_i}$ multiplied by the unsteered Fast Fourier Transform. If we look at equations given by [2], we can write this as a vector equation:

$$Y(f) = \boldsymbol{d}^H(\theta, f)\boldsymbol{W}\boldsymbol{x}(f) \tag{5}$$

Here, θ is the incident angle, $\boldsymbol{W}$ is a weighting matrix:

$\boldsymbol{d}^{H}(\theta, f)$ is a steering vector which depends on incident angle, frequency, element spacing, and speed of sound:

and $\boldsymbol{x}(f)$ is the data vector:

We can use this knowledge to apply a far-field beamforming algorithm to our data. This allows us to create a bearing-time record of a specific run over a certain period of time.

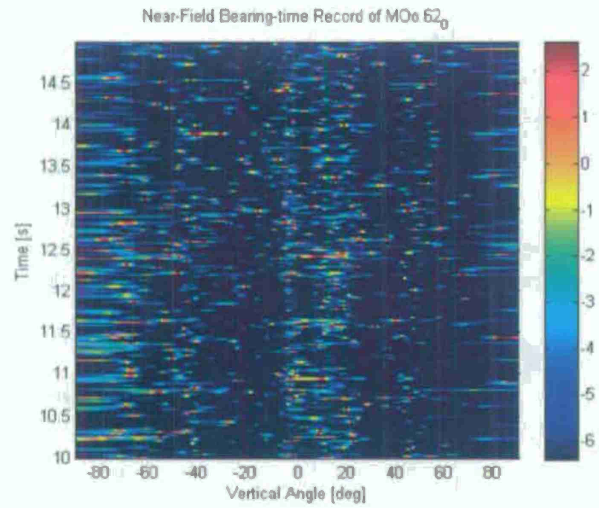

Figure 3. Bearing-Time Record of broadband noise generated by a J9 omnidirectional source in shallow water over a 5 second window.

Figure (3) shows us the strongest angles of incidence from the source (presumably the direct path, and first reflections off the surface and bottom interface). Averaging these levels over the time window, we are able to see the contributions from each path at each angle.

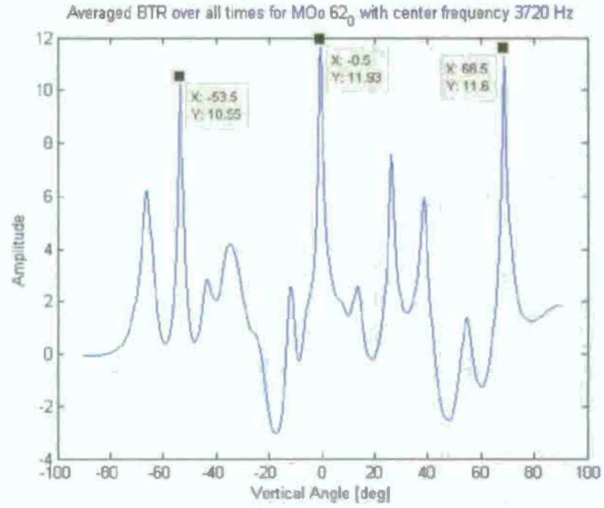

Figure 4. Average of Figure (3) over the 5 second time window.

In Figure (4) we can see three distinct paths, likely the direct path, surface reflection, and bottom reflection. However, we can also see that this is muddied with other reflections as well. We also now know the direction of the noise source, but not the actual location, specifically the range. This is crucial in determining the transmission loss, and ultimately the source noise level.

NEAR-FIELD BEAMFORM PROCESSING

Far-field beamforming, while quite convenient and accurate in far-field, free-field measurements, loses its precision in multipath, near-field environments where far-field assumptions cannot be made. Once again, starting with Equation (1), we can use some basic geometry to eliminate the far-field assumptions and account for the curvature of the wave front. We will also measure from the geometric center of the array, instead of the top-most element.

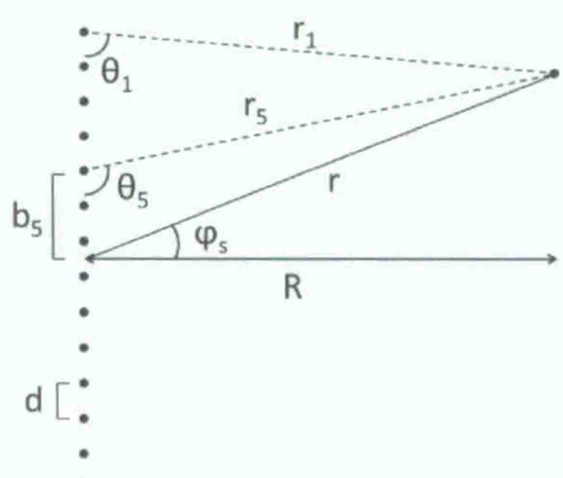

Figure 5. Test site geometry that includes near-field paths.

Figure (5) shows the geometry of this near-field problem and gives us a relatively easy method of determining a phase shift. Recalling that the phase shift:

This time, we cannot assume that all r_i are equal, so where r_i is the distance from the source to each individual element and r is the distance from the center of the array to the source. The distance r can be represented by:

We can then use the distance from each individual element to the center of the array:

(6)

where N is the total number of elements, i is the element number, and d is the separation distance between each element, and the law of cosines to find the distance from each element to the source:

(7)

The angle steering angle for each individual element is also no longer constant, and can be determined by:

(8)

This can now be used in Equation (1) to find the specific pressure without making any far-field assumptions. Once again we can take an FFT of this equation to find:

(9)

Once again, it appears the only addition to the unsteered FFT is a phase delay term, , that is dependent on both steering angle, ϕ_s, and range, R.

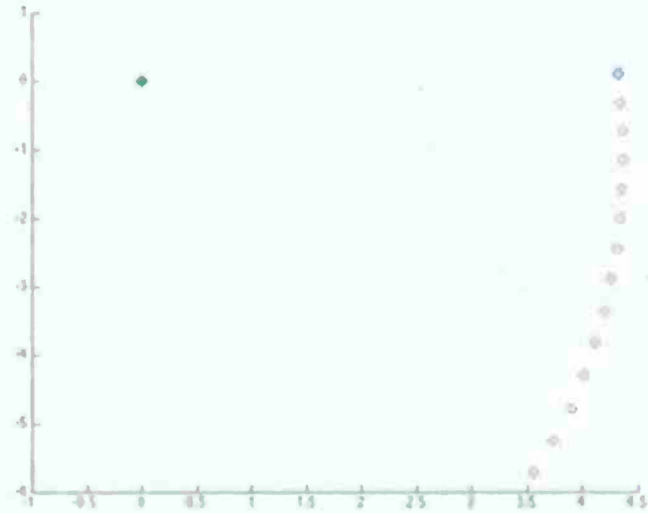

Figure 6. Illustration of the array with the source normalized to the origin and highlighted in green. The top hydrophone is highlighted in blue because it is shallower than the source. This array shape agrees with visual observations of the array out of the water. The distortion in the shape of the array is likely caused by the weight of the cables and hydrophones causing stress on the array. Units on each axis are meters.

A complication in this method lies in the error of precise knowledge of the array element locations. Using other methods of source localization, we determined that our array was not, in fact, perfectly linear. Instead, it more resembled the shape shown in Figure (6). This shows a max difference of nearly one meter between the bottom element and one of the topmost elements. With wavelengths in our range of interest, this location difference can change the initial phase of the signal enough that it voids the phase shift that we are trying to apply.

These have not yet been implemented, however, much research suggests that near-field beamforming will reduce side-lobe contribution even more and allow us to determine the source noise level with the most accuracy.

CONCLUSIONS

Underwater noise source radiation is difficult to characterize in a shallow water environment where multiple paths contribute largely to the overall noise level. We have presented various degrees of measurement and processing skills that ultimately may be able to accurately determine the noise source level of an object in this environment when nothing is known about the object. Further investigation will determine just how accurate the near-field approach will actually be in solving the problem of source radiation in this complicated environment.

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2. Abraham, D. A. "Array Signal Processing for Sonar: Short Course." Proc. of 159th Meeting of the Acoustical Society of America, Baltimore, MD. Print

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